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### 54 Near-field photon tunnelling devices.

57 The near-field photon tunneling devices consist of a plurality of optical waveguides, such as optical fibers (1, 2), arranged in juxtaposition with a variable tunnel gap (13) through which photons from at least one of said optical fibers (1, 2) can be caused to tunnel, and wherein the said tunnel gap (13) is filled with a metal (16) that is liquid at room temperature or at moderately elevated temperature. The width of the tunnel gap (13), -and with it the thickness of the liquid metal layer- is remotely controllable. The proposed control mechanisms include optical means, piezo-electric elements (8) and temperature-sensitive means.

The devices proposed include optical couplers of the head-on and side-on types, optical modulators and switches, as well as display units.

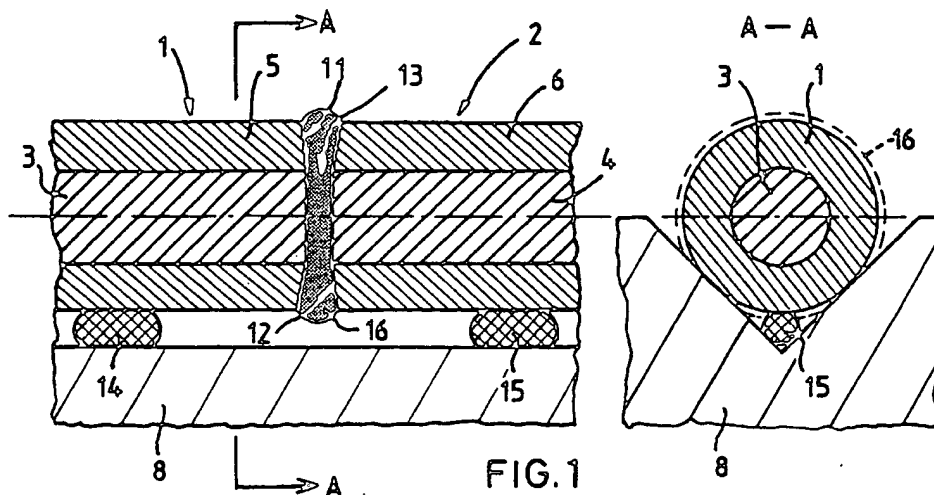


FIG. 1

This invention relates to near-field photon tunneling devices, i.e., to devices that permit controlled transfer of photons from one transmission medium to another, where the control is implemented through mechanically regulating the tunneling of the photons through a potential barrier. The invention is applicable in the field of information processing where the transfer of information-carrying lightwaves between two or more transmission media, or between a transmission medium and an observer's eyes, is being controlled.

In particular, the invention is directed to devices permitting the controlled transfer of photon energy between two or more optical waveguides, such as glass fibers or other light transmitters, namely to optical couplers, optical modulators and optical switches. To cope with the mounting flood of information and data which have to be transmitted over ever increasing distances at growing speed, all of which can be handled only with broadband transmission media that allow the highest transmission rates and yet have the least losses, communication techniques employing glass fibers have been developed which rapidly replace existing electronic communications technology down to the private branch exchange level. Devices in glass fiber technology, therefore, enjoy increasing attention.

The information transmission capabilities of optical fibers are well known in the art, and a very large number of optical devices for the connection of optical fibers to transmitter and receiver, as well as with other optical fibers are known in the art. The following references are examples for proposals of optical couplers, modulators and switches, including their theoretical aspects:

- a. A.L. Jones, "Coupling of Optical Fibers and Scattering in Fibers", J. Opt. Soc. Am. Vol. 55, No. 3, March 1965, pp. 261-271.
- b. A.W. Snyder, "Coupled-Mode Theory for Optical Fibers", J. Opt. Soc. Am. Vol. 62, No. 11, Nov. 1972, pp. 1267-1277.
- c. M. Papuchon et al., "Electrically switched optical directional coupler: Cobra", Appl. Phys. Lett. Vol. 27, No. 5, Sept. 1975, pp. 289-291.
- d. T. Findakly et al., "Optical directional couplers with variable spacing", Applied Optics Vol. 17, No. 5, March 1978, pp. 769-773.
- e. Y. Tsujimoto et al., "Fabrication of Low-Loss 3dB Couplers with Mulyimode Optical Fibers", Electron. Lett. Vol. 14, No. 5, March 1978, pp. 157-158.
- f. S.K. Sheem et al., "Single-mode fiber-optical power divider: encapsulated etching technique", Optics Lett. Vol. 4, No. 1, Jan. 1979, pp. 29-31.
- g. R.A. Bergh et al., "Single-Mode Fibre Optic Directional Coupler", Electron. Lett. Vol. 16, No. 7, March 1980, pp. 260-261.
- h. O. Parriaux et al., "Distributed coupling on polished single-mode optical fibers", Appl. Optics Vol. 20, No. 14, July 1981, pp. 2420-2423.
- i. M.J.F. Dignonnet et al., "Analysis of Tunable Single Mode Optical Fiber Coupler", IEEE J. of Quantum Electronics, Vol. QE-18, No. 4, April 1982, pp. 746-754.
- j. E.S. Goldburt et al., "Non-Linear Single-Mode Fiber-Coupler Using Liquid Crystals", IBM Research Report RC 10865, May 1984.
- k. A.K. Das et al., "Analysis and modelling of low loss fused fiber couplers", Proc. SPIE-Intl. Soc. Opt. Eng. Vol. 1365, 1991 pp. 74-85.
- l. G.-D. Peng et al., "Modified Gaussian approach for the design of optical fiber couplers of arbitrary core shapes", Appl. Optics Vol. 30, No. 18, June 1991, pp. 2533-2545.
- m. A.W. Snyder et al., "Physics of nonlinear fiber couplers", J. Opt. Soc. Am. B, Vol. 8, No. 10, Oct. 1991, pp. 2102-2118. C.C. Yang, "All optical ultrafast logic gates that use asymmetric nonlinear directional couplers", Opt. Lett. Vol. 16, No. 21, Nov. 1991, pp. 1641-1643.
- n. G. Fawcett et al., "In-Line Fibre-Optic Intensity Modulator Using Electro-Optic Polymer", Electron. Lett. Vol. 28, No. 11, May 1992, pp. 985-986.

Most of the conventional optical devices are intended for total optical power transfer and, therefore, rely on stationary arrangements of their components. The present invention is distinguished from most of these prior art references in that it provides for mechanical control of the coupling between the optical transmission media. Partial power coupling between single-mode fibers, for example, is difficult to realize since the actual fabrication of an evanescent-field type coupler is tedious because the fiber core diameter is only a few micrometers, and the fiber is buried deep inside the cladding which is typically only 0.1 mm in diameter.

The Dignonnet reference (i) describes a tunable single-mode coupler where the two halves of the coupler are placed in a holder provided with micrometric screws that permit to adjust the mutual position of those halves and with it the strength of the coupling between the fibers. A different type of tunable coupler is described in the Fawcett reference (m). Here, the coupling strength is controlled by an electric field across an electro-optic polymer that is placed in the evanescent field of an optical fiber. Variation of the electric

field causes corresponding variation of the refractive index of the polymer, thus leading to intensity modulation in the fiber or in the light collected from the polymer, at a particular wavelength.

While the device of the Digonnet reference (i) is obviously meant for a single adjustment, i.e., it would be impractical to readjust the setting of the micrometer screw during operation, the Fawcett reference (o) does not show how the optical energy could be coupled between two optical fibers. It is an object of the present invention to improve on these devices and to provide optical coupling devices in the broad sense of this term, with remotely tunable coupling characteristics.

Accordingly, the present invention teaches near-field photon tunneling devices comprising at least two optical waveguides, such as optical fibers, arranged in juxtaposition with a variable tunnel barrier through which photons from at least one of said optical waveguides can be caused to tunnel, and wherein the said tunnel barrier consists of a gap of controllable width containing a layer of liquid metal. Such liquid metal layer may consist of a metal selected from the group comprising gallium, indium, mercury and their alloys.

Details of several embodiments of the invention will hereafter be described by way of example, and with reference to the attached drawings in which:

- 15 *Fig. 1* shows longitudinal and cross sections of a head-on optical coupler in accordance with the invention;
- Fig. 2* is scheme showing the arrangement of the optical fibers in a side-by-side optical coupler;
- Fig. 3* is an enlarged view of the coupling portion of the coupler of *Fig. 2*;
- Fig. 4* depicts a head-on coupler in accordance with the invention;
- 20 *Fig. 5* shows a side-on optical coupler;
- Fig. 6* shows another embodiment of a side-on optical coupler;
- Fig. 7* illustrates a bistable coupling device;
- Fig. 8* shows a visual display unit employing coupling devices of the type shown in *Fig. 4*.

In accordance with the invention, electro-optic and opto-optic devices, such as, for example, couplers, modulators and switches, can be realized on the basis of the physical phenomenon known as "near-field optics" (NFO), in particular with the aid of photon tunneling through a variable tunnel barrier. In this connection, the gist of the invention resides in the employ of a liquid metal as the constituent of the variable tunnel barrier in those optical devices.

The liquid metal combines two characteristics that are essential in the realization of the devices in accordance with the invention: (1) The metal being liquid at operating temperature (be it room temperature or a moderately elevated temperature) is highly deformable and, thus, allows easy variation of the thickness of a layer of liquid metal within the tunnel gap, and (2) the liquid metal has a very high absorption coefficient so that very little variation of the thickness of the metal layer results in a very large change in the optical coupling: A thickness variation of between 20 and 40 nm is sufficient to alter the photon transmission through the liquid metal by a factor of 10 to 100.

The thickness variation is easiest produced by adjusting the tunnel gap width between the optical waveguides involved. Considering that the amount of mutual displacement required is on the order of tens of nanometers only, and that the displacement should be reproducible, there are two preferred ways of producing the required mechanical shift:

- 40 - by piezo-electric elements,
- by heating and thermal expansion.

A combination of the two schemes is possible and will be explained below.

The description will now turn to the design of the different NFO devices of the invention. For ease of explanation, the embodiments of the invention selected for discussion below pertain to the group working with optical fibers, but it will be obvious to those skilled in the art how to apply the principles of the invention to other types of waveguides. The first device to be described is the head-on electro-optic fiber coupler shown in *Fig. 1*. Optical fibers 1 and 2 consisting, as usual, of glass fiber cores 3 and 4, respectively, and their claddings 5 and 6, are placed butt-joint in a straight slot 7 machined into the surface of a support 8, and rest on the flanks 9 and 10 with the axes of their cores 3, 4 perfectly aligned. Alternatively, the optical fibers 1 and 2 can be arranged coaxially within a common tubular precision mount similar to that of a conventional optical fiber connector.

The ends 11 and 12 of optical fibers 1 and 2 are polished to form flat faces across the area of the cores 3, 4. Preferably, the end faces of claddings 5, 6 are given a slightly convex shape as shown in *Fig. 1*. The gap 13 is then filled with liquid metal 16. Liquid metal as gap filling provides for reproducible gap deformation. As the width of gap 13 is varied during operation, the liquid metal 16 must be able to "breathe". In the arrangement where optical fibers 1 and 2 are arranged on slot 7, there is enough space around the fibers for the liquid metal to be extruded from the gap. In case of placement of the fibers inside a tubular mount, the tube must be provided with a hole in the region of the gap to allow for volume variation

of the liquid metal 16 as the gap width is changed. Or else the tube must be provided with a flexible portion in juxtaposition with the gap. Whatever the arrangement may be, it must allow a variation of the gap width on the order of 50 nm.

Several metals, in particular alloys, are known to be liquid at, or near, room temperature. Examples are:  
 5 Indium/gallium eutectic alloy with a melting point at 15.7°C, indium/mercury alloys with up to 70% indium, or pure gallium with a melting point at 29°C, or pure mercury. Also, more complicated alloys, such as ternary or higher compositions are known to be liquid at room temperature or a somewhat elevated temperature, say up to about 300°C. For more information on liquid metals, reference is made to M. Hansen et al., *Constitution of Binary Alloys*, McGraw-Hill Book Company, Inc., New York 1958, in  
 10 particular pp. 745-747.

In order to maintain a stable fluid film between the end surfaces 11, 12 of the optical fibers 1 and 2, even at very small gap widths, it is necessary that the liquid metal 16 wet the glass fiber and/or the cladding material, at least to a certain extent. The properties of Ga/In alloy are favorable in this respect, for example, in contrast to pure mercury, since clean dry surfaces of glass and similar materials, such as the  
 15 usual cladding material, are readily wetted. Also, metallized surfaces are wetted without a problem. It may, therefore, be advantageous to coat the end surfaces 11, 12 of the optical fibers with a thin metal film, such as gold or chromium, for example.

The wetting requirement can also be met in other ways. There is a large variety of chemical and mechanical surface preparation techniques available to achieve wettability. Also, since these devices are  
 20 anyway encapsulated in a sealed casing, hydrostatic pressure may be applied to improve wetting.

Ideally, the adhesion between the liquid metal 16 and the end surfaces 11, 12 is positive but small, lest the fluid motion is hampered by surface effects. Gap 13 may be filled under vacuum conditions. The mechanical forces of acceleration, and viscous flow, estimated on the basis of classical hydrodynamics, are negligibly small compared to the forces generated by piezo-electric elements.

The liquid metal 16 disposed between end surfaces 11 and 12 takes the form of a very thin film. An optical wave passing through a thin metallic film is heavily attenuated. The penetration depth  $z_0$  (defined as the 1/e intensity decay length) for the photons typically is  $z_0 = 5 \dots 20 \text{ nm}$ . It will, therefore, be sufficient if a displacement in the range of 2 to 6 decay lengths  $z_0$  between the said end surfaces is possible. This displacement can be reproducibly achieved by means of a piezo-electric element to which optical fibers 1  
 30 and 2 are fixed. For example, support 8 may consist of a piezo-electric material, and optical fiber 1 may be assumed to be glued thereto, as indicated by the droplet of glue 14, and optical fiber 2 is likewise glued to support 8 by means of a droplet of glue 15. Application of an electrical potential across support 8 in the region between droplets 14 and 15 will cause gap 13 to be varied in dependence on the polarity and amplitude of the said potential.

Ceramic piezo-electric elements, such as, for example, tubes of 2 mm diameter, with a wall thickness of 0.4 mm, a length of 10 mm and having a piezo-electric coefficient of about  $10^{-10} \text{ m/V}$  (which corresponds to a conversion efficiency  $\Delta z/\Delta U = 2.5 \text{ nm/V}$ .) are commercially available. The operating voltage for these elements is, thus, far less than 100 V. Because of its small dimensions, the assembly - comprising the end sections of the optical fibers and support 8 - will have a high mechanical resonance frequency ( $> 30 \text{ kHz}$ )  
 40 corresponding to short response times ( $< 100 \mu\text{s}$ ).

For initial alignment of the tunable optical fiber coupler being described, the ends of fibers 1 and 2 are brought in physical contact with each other while a contracting potential corresponding to about  $3z_0$  ( $\approx -15 \text{ V}$ ) is applied to the electrodes of the piezo-electric support 8. The glue is then applied and allowed to harden. When the potential is removed, support 8 will relax, and the gap between optical fibers 1 and 2 will  
 45 be about 30 nm wide. With the application of potentials between  $+15 \text{ V}$  and  $-15 \text{ V}$ , the coupling between fibers 1 and 2 can be adjusted from about 0% (corresponding to  $\approx 6z_0$ ) to 100% at physical contact.

If the electrodes of piezo-electric support 8 are fed with an alternating potential of 15 V amplitude, the arrangement described can be operated as a modulator. With the piezo-electric tube described above, an upper frequency of  $> 30 \text{ kHz}$  appears possible.

The same arrangement of optical fibers 1, 2 and support 8 can be operated as an optical switch. For a  
 50 NORMAL ON type switch, fibers 1 and 2 are brought in physical contact with no potential applied to support 8. After the glue has hardened, the application of a potential corresponding to  $6z_0$  will cause the switch to disrupt the coupling between fibers 1 and 2 completely. Conversely, when a potential corresponding to  $6z_0$  is applied while the glue is hardening, the switch will be in the NORMAL OFF state when the potential is removed. Reference is now made to Fig. 2 which shows a conventional side-on electro-optic fiber coupler of  
 55 the type shown in Fig. 1b of the Dignonnet reference (i). Two optical fibers 18, 19 are mounted between two appropriately slotted blocks 20 and 21, with the cladding of the fibers removed at the portions of the fibers arranged closest to each other to such an extent that the cores 22 and 23 are exposed over a distance of

about one millimeter. In accordance with the invention, the mutual distance between the cores is on the order of several  $z_0$ , as shown in Fig. 3. The space between cores 22 and 23 is filled with liquid metal 24. A piezo-electric bimorph slab 25 (such as those mass-produced for buzzer applications, for example) is rigidly mounted on block 21 so as to touch on optical fiber 19 with its convex side.

5 As a potential is applied to it, bimorph 25 expands, thus pressing against fiber 19 which in turn bends to narrow the gap between it and fiber 18, thinning the liquid metal layer 24. Again, the degree of optical coupling between fibers 18 and 19 depends on their separation and on the attenuation characteristics of the liquid metal. Because of the very small values of the optical decay length in metals, tiny variations of the mutual separation between the fibers are sufficient for large changes in coupling. For example, an  
10 exemplary bimorph as short as 6 mm, and 0.5 mm thick, can provide a deflection of about 10 nm/V.

The initial setting of this coupler can be chosen such that at zero potential at bimorph 25, the thickness of the liquid metal layer 24 exceeds  $6 z_0$ . Light entered into any one of fibers 18 or 19, no matter at which end thereof, will pass the coupler essentially unaffected and exit from the remote end of the same fiber unattenuated. There will be no coupling of light into the paired fiber. With potential applied to bimorph 25,  
15 the thickness of the liquid metal layer 24 will be decreased correspondingly, and light will be coupled from the input fiber into the paired fiber. Assuming lossless conditions (not realistic in practical applications, however), a maximum of 50% of the input light energy will be transferred onto the paired fiber.

To render this coupler heat-controllable, bimorph 25 will simply have to be replaced by a bimetal element. The initial setting of the bimetal element can follow the principles of a thermostat setting. This will  
20 lead to a temperature-dependent variation of the coupling degree.

The next device to be described is the head-on all-optic fiber coupler shown in Fig. 4. The optical fibers 27 and 28 are rigidly fixed in a support 29 with a small gap 30 between their ends. Gap 30 is filled with a liquid metal 31. The end section 32, of a length  $l_1$ , of the optical fiber 27 on the input side of the coupler is doped so as to absorb radiation at a frequency  $\nu_1$ , and it is thinned down to a radius of  $\approx 10 \mu\text{m}$ . The  
25 radiation  $\nu_1$  can either come from a signal laser (with a frequency  $\nu_1$ ), and then the coupler acts as a non-linear optical element, or from a second emitter (pump laser with a frequency  $\nu_1$ ). In the latter case, the transmission of the signal at frequency  $\nu_2$  outside the absorption band is switched by the pump laser.

Considering the case of the pump laser-actuated coupler: When it becomes exposed to the pump radiation, end section 32 expands by  
30

$$\Delta l = \alpha_1 l_1 \Delta T, \quad [1]$$

thereby closing gap 30. ( $\alpha_1$  = coefficient of linear thermal expansion.) The temperature increase  $\Delta T$  is given by the balance of absorbed power per unit length  
35

$$\hat{P} = \int p(\vec{r}) dA$$

and of the heat diffused to the surrounding liquid metal bath which acts as a heat sink. Here  $p(\vec{r})$  is the  
40 locally absorbed power density and  $dA$  an element of the cross-sectional area  $A$ . Power consumption and switching speed are governed by the equation of heat diffusion:

$$\rho C_p \dot{T}(\vec{r}) = K \nabla^2 T(\vec{r}) + p(\vec{r}) \quad [2]$$

45 where  $\rho C_p$  and  $K$  are the specific heat per unit volume and the heat conductivity, respectively.

An order of magnitude estimate is obtained by assuming that  $p$  and  $\Delta T$  depend on the radial coordinate  $r$  only, by setting  $\nabla^2 T(r) = \Delta T/R^2$  and

$$\vec{p}(r) = \hat{P}/R^2, \quad 50$$

and by considering stationary conditions,  $T = 0$ . The combination of equations [1] and [2] yields for the entire energy dissipated in the HOLD state:  
55

$$P_{\text{HOLD}} = \hat{P} l_1 = \left( \frac{K}{\alpha_1} \right) \Delta z, \quad [3]$$

where  $\Delta z = -\Delta l$ . The TURN-ON time is very short, given essentially by the velocity  $v$  of sound:

$$\tau_{ON} = \frac{l_1}{v} \quad [4]$$

The TURN-OFF time is limited by the cooling rate:

$$\tau_{OFF} = R^2 \rho C_p / K. \quad [5]$$

In Table 1 the relevant parameters are put together for three types of fibers, while Table 2 shows the resulting values for temperature rise, energy consumption, switching times, and the product of power and delay ( $P_{HOLD} \times \tau_{OFF}$ )

A small value of  $R$  is favorable for fast heat transfer. The value of  $R = 10 \mu\text{m}$  chosen here for the fiber radius is roughly determined by the extension of the fundamental fiber mode.  $\Delta z = 30 \text{ nm}$  is a typical value required for nearly complete change of transmission. The length  $l_1 = 1 \text{ mm}$  of the doped end section 32 is chosen to be sufficiently small for a stable setup of reasonable size, but may be varied over a fairly wide range.

The energy consumption for the two inorganic glasses is relatively large, caused mainly by the small thermal expansion coefficients. The organic glass PMMA, however, provides an attractively low power consumption. The switching time  $\tau_{OFF}$  is relatively slow in all three cases, limiting the device to applications requiring infrequent switching only.

**TABLE 1 Fiber Parameters**

Type of Fiber	Fused Quartz	Reg. Glass	PMMA
<b>Parameters</b>			
Core Radius [ $\mu\text{m}$ ]	3	3	3
Effect. Radius $R$ [ $\mu\text{m}$ ]	10	10	10
Lin. Therm. Expan. $\alpha_1$ [ $\text{K}^{-1}$ ]	$5 \times 10^{-6}$	$10^{-4}$	$10^{-4}$
Heat Conduct. $K$ [ $\text{W/Km}$ ]	1	1	0.2
Spec. Heat (Vol.) $\rho C_p$ [ $\text{J/Km}^3$ ]	$2 \times 10^6$	$2 \times 10^6$	$1.5 \times 10^6$
Sound Velocity $v$ [ $\text{m/s}$ ]	5500	4200	2600
<b>Figures of Merit:</b>			
$K/\alpha_1$ [ $\text{W/m}$ ]	$2 \times 10^5$	$10^5$	$2 \times 10^3$
$K/\rho C_p$ [ $\text{m}^2/\text{s}$ ]	$5 \times 10^{-7}$	$5 \times 10^{-7}$	$10^{-7}$
<b>Values chosen:</b>			
Active Length $l$ [ $\text{mm}$ ]	1	1	1
Elongation $\Delta l$ [ $\text{nm}$ ]			
Head-on:	30	30	30
Side-on:	100	100	100

TABLE 2

Performance Data - Head-On Coupling			
Type of Fiber Parameters	Fused Quartz	Reg. Glass	PMMA
$\Delta T$ [K]	20	10	1
$P_{HOLD}$ [ $\mu W$ ]	2000	1000	20
$\tau_{ON}$ [ $\mu s$ ]	0.2	0.2	0.5
$\tau_{OFF}$ [ $\mu s$ ]	200	200	1000
$P_{HOLD}\tau_{OFF}$ [nJ]	400	200	20

Another embodiment of the invention is the side-on all-optic fiber coupler shown in Fig. 5. Optical fibers 34 and 35 are arranged in close proximity, almost sufficiently close for coupling, with fiber 34 being supported between fixed posts 36 and 37, yet free to expand, and with fiber 35 being attached to a support 38. The distance  $l_2$  between posts 36 and 37 is chosen to be somewhat larger than the (longitudinal) interaction length  $l_i$  typically in the range of 0.1 to 1 mm. In the region of juxtaposition of fibers 34, 35, the cladding diameter is reduced to a value appropriate for waveguide coupling, i.e. about 10  $\mu m$ . The section 39 of optical fiber 34 that extends between posts 36 and 37 is doped or otherwise made absorbant for a pump radiation. The space between posts 35, 36, i.e. along section 39, is filled with a liquid metal 40.

With a pump radiation entered into fiber 34, energy is absorbed in section 39 thereof, and that section expands, moving sideways and undergoing a displacement  $\Delta z$ :

$$\Delta z \approx \sqrt{l_2 \Delta l} = l_2 \sqrt{\alpha_1 \Delta T}. \quad [6]$$

The result of this displacement is, of course, a modification of the distance between fibers 34 and 35 and, hence a variation of the coupling coefficient.

Relation [6] indicates that the temperature increment for a certain  $\Delta z$  is  $\Delta l/l$  times smaller than in the case of the head-on coupler. The requirements with regard to power consumption hence are greatly relaxed, allowing operation with inorganic glass fibers, and giving plenty of latitude with regard to the choice of design parameters. For a numerical estimate, the same values as are chosen for the parameters, except for the displacement which is assumed to be as large as  $\Delta z = 100$  nm. The larger value allows for making smooth contact between fibers 34 and 35 over an extended length. The resulting operating parameters are compiled in Table 3:

TABLE 3

Performance Data - Side-On Coupling			
Type of Fiber Parameters	Fused Quartz	Reg. Glass	PMMA
$\Delta T$ [K]	0.002	0.001	0.0001
$P_{HOLD}$ [ $\mu W$ ]	0.6	0.3	0.006
$\tau_{ON}$ [ $\mu s$ ]	0.2	0.2	0.5
$\tau_{OFF}$ [ $\mu s$ ]	200	200	1000
$P_{HOLD}\tau_{OFF}$ [nJ]	120	60	6

Still another embodiment of the invention is the coupler shown in Fig. 6. An absorbing section 42 is part of an optical fiber 43 which is connected to a source of pump radiation 44. The ends of section 42 are attached respectively to optical fibers 45 and 46 by means of a pair of clamps 47 and 48. The gap between signal fibers 45 and 46 is filled with a liquid metal 49. Section 42 will expand in proportion to the power of the pump radiation. The resultant modulation of the signal passing through the liquid metal 49 will be exponential.

A further embodiment of the invention is depicted in Fig. 7. Optical fibers 51 and 52 are fixed in a support 53, with a section 54 with a length  $l_3$  of fiber 52 being doped to be absorbant at the operating frequency of the device. The gap between fibers 51 and 52 is filled with a liquid metal 55. With the signal radiation applied to fiber 51, the power level inside section 54 depends on the product of the power of the signal source and of the transmission of the liquid metal. The transmission in turn is a function of

temperature and, hence, of the power inside section 54. This is a typical condition for a bistable operation.

The invention is also applicable to display devices. Fig. 8 shows an embodiment of a matrix display unit in which a matrix of  $M \times N$  optical fibers 57 is arranged in a way similar as in the head-on couplers described above. The fibers 57 are rigidly fixed in a mounting plate 58 and slidably supported in an  $M \times N$  matrix of holes 59 in a support plate 60. When all fibers 57 are in their home position, their ends are in one common plane (as a result of polishing, for example), just by a minute distance extending from the surface of support plate 60. The distance between the mounting and support plates 58, 60 is chosen so as to provide for an ample amount of expansion of absorbant sections 61 of the fibers 57 as optical energy is applied to them. Mounted parallel to support plate 60 is a ground glass plate 62, on its side facing said support plate 60 carrying a thin film 63 of liquid metal. The spacing between said support and glass plates 60, 62 is adjusted so that the ends of optical fibers 57 dip into the liquid metal.

In operation, when optical energy is applied to selected ones of fibers 57, the ensuing expansion of their respective sections 61 causes the thickness of the liquid metal film 63 between the ends of fibers 57 and the associated region of glass plate 62 to become reduced and thus more penetrable for the photons from those selected fibers. Accordingly, an image will be formed on ground glass plate 62 which corresponds to the pattern of selected, i.e. energized optical fibers 57, with the brightness of the picture points depending on the intensity of the light entered into the fibers 57 involved.

### Claims

1. Near-field photon tunneling devices comprising at least two optical waveguides (1, 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57) arranged in juxtaposition with a variable tunnel barrier through which photons from at least one of said optical waveguides (1, 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57) can be caused to tunnel, **characterized** in that said tunnel barrier consists of a gap (13, 30) of controllable width containing a layer of liquid metal (16, 24, 31, 40, 49, 55, 63).
2. Photon tunneling devices in accordance with claim 1, **characterized** in that said liquid metal layer (16, 24, 31, 40, 49, 55, 63) consists of a metal selected from the group comprising gallium, indium, mercury and their alloys.
3. Photon tunneling devices in accordance with claim 1, **characterized** in that the optical waveguides (1, 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57), at least in their area of exposure to the liquid metal, are coated with a film of a material which improves their wettability by said liquid metal (16, 24, 31, 40, 49, 55, 63).
4. Photon tunneling devices in accordance with claim 1, **characterized** in that the optical waveguides (1, 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57), at least in their area of exposure to the liquid metal, are coated with a thin film of a metal selected from the group comprising gold and chromium, to improve their wettability by said liquid metal (16, 24, 31, 40, 49, 55, 63).
5. Photon tunneling device in accordance with claim 1, **characterized** in that said optical waveguides (1, 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57) are optical fibers.
6. Photon tunneling device in accordance with claims 1 and 5, **characterized** in that two optical fibers (1, 2) are rigidly mounted on a length-variable support (8) with their end surfaces (11, 12) facing each other with a tunneling gap (13) in between and with their axes aligned, that said gap (13) is filled with a liquid metal (16), and that said support (8) consists of a variable-length actuator the elongation/contraction of which can be remotely controlled so as to allow operation as a head-on optical coupler with controllable coupling coefficient.
7. Photon tunneling device in accordance with claims 1 and 5, **characterized** in that two optical fibers (1, 2) are rigidly mounted on a length-variable support (8) with their end surfaces (11, 12) facing each other with a tunneling gap (13) in between and with their axes aligned, that said gap (13) is filled with a liquid metal (16), and that said support (8) consists of a thermal expansion element the elongation/contraction of which can be remotely controlled so as to allow operation as a head-on optical coupler with controllable coupling coefficient.



8. Photon tunneling device in accordance with claims 1 and 5, **characterized** in that two optical fibers (1, 2) are rigidly mounted on a length-variable support (8) with their end surfaces (11, 12) facing each other with a tunneling gap (13) in between and with their axes aligned, that said gap (13) is filled with a liquid metal (16), and that said support (8) consists of a piezo-electric element the elongation/contraction of which can be remotely controlled so as to allow operation as a head-on optical coupler with controllable coupling coefficient.
9. Photon tunneling device in accordance with claim 5, **characterized** in that the end surfaces (11, 12) of said optical fibers (1, 2) are polished optically flat across their cores (3, 4), with the end faces of their claddings (5, 6) having slightly convex shape providing for a gap (13) whose width increases in radial direction.
10. Photon tunneling device in accordance with claim 5, **characterized** in that two optical fibers (18, 19) are fixed side-on between two slotted blocks (20, 21) with a liquid metal (24) filling the tunnel gap between said fibers (18, 19) along a section thereof where their cladding is removed to expose their cores (22, 23), and that a remotely controllable actuator (25) is arranged for cooperation with one (19) of said fibers (18, 19) so as to control the thickness of said liquid metal filling (24) when actuated, to enable operation as a side-on electro-optical fiber coupler with controllable coupling coefficient.
11. Photon tunneling device in accordance with claim 5, **characterized** in that two optical fibers (27, 28) are fixed head-on, axes aligned, in a support (29) with the tunnel gap (30) between their ends filled with a liquid metal (31), and with a section (32) of the fiber (27) associated with the input of the device being radiation-sensitive, so as to vary the width of the tunnel gap (30) in dependence on the input radiation, enabling the operation of the device as a radiation-controlled switch.
12. Photon tunneling device in accordance with claim 5, **characterized** in that a first optical fiber (34) having a radiation-sensitive section (39) is arranged between a pair of fixtures (36, 37) so as to be able, upon application of a radiation, to bend towards a second optical fiber (35) fixed side-on at tunneling distance from said first optical fiber (34) along a common interaction length ( $l_i$ ), that the cladding diameter of said optical fibers (34, 35) is reduced at least along said common interaction length ( $l_i$ ), and that the gap between said optical fibers (34, 35) and at least along said interaction length ( $l_i$ ) is filled with a liquid metal (40), the device forming a side-on all-optic fiber coupler with radiation controlled coupling coefficient.
13. Photon tunneling device in accordance with claim 5, **characterized** in that a first optical fiber (43) having a radiation-sensitive section (42) and connected to a source of pump radiation (44) is arranged side-on with second and third optical fibers (45, 46) which on their part are arranged in mutual axial alignment with their ends forming a tunnel gap, said gap being filled with a liquid metal (49), said second and third optical fibers (45, 46) being clamped (47, 48) to said first optical fiber (43) along its radiation-sensitive section (42), the device forming a side-on all-optic fiber coupler with pump radiation-controlled coupling and exponential coupling coefficient response.
14. Photon tunneling device in accordance with claim 5, **characterized** in that a plurality of optical fibers (57) is fixed in a mounting plate (58) in an  $M \times N$  matrix pattern, the fibers (57) having absorbant end sections (61) extending beyond said mounting plate (58) and across a gap between said mounting plate (58) and through holes (59) ordered in the said  $M \times N$  matrix pattern in a support plate (60) fixed parallel with said mounting plate (58), the length-aligned end sections (61) of said fibers (57) dipping into a thin film (63) of liquid metal coated onto a ground glass plate (62) in turn arranged parallel with and at tunnel distance from said support plate (60), the arrangement being such that upon application of radiation to selected ones of said optical fibers (57), their end sections (61) elongate to decrease the thickness of said thin film 63 at their respective location, forming a visible image on the far side of said ground glass plate (62).
15. Photon tunneling device in accordance with claim 1, **characterized** in that the waveguides are enclosed in a casing to which hydrostatic pressure is applied to improve wetting of the waveguides (1 2; 18, 19; 27, 28; 34, 35; 45, 46; 51, 52; 57) by the liquid metal (16, 24, 31, 40, 49, 55, 63).

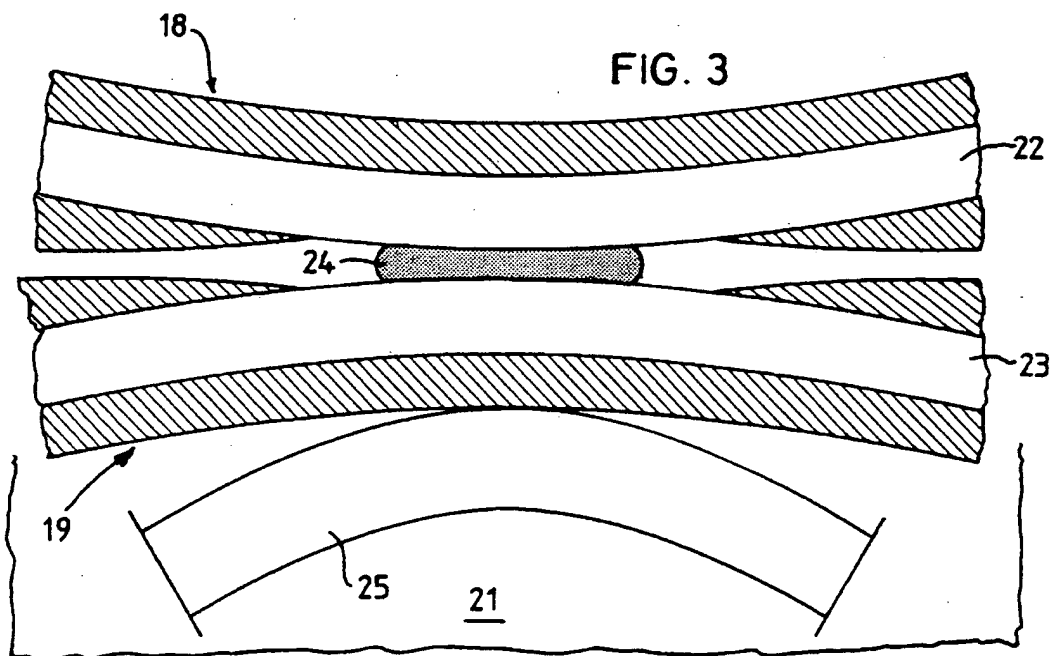
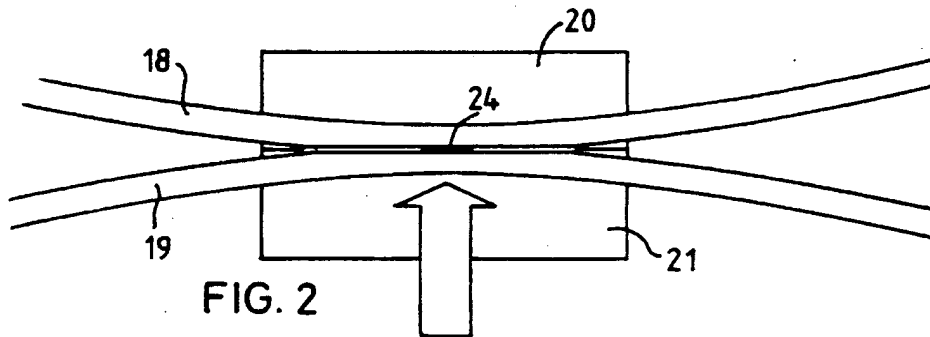
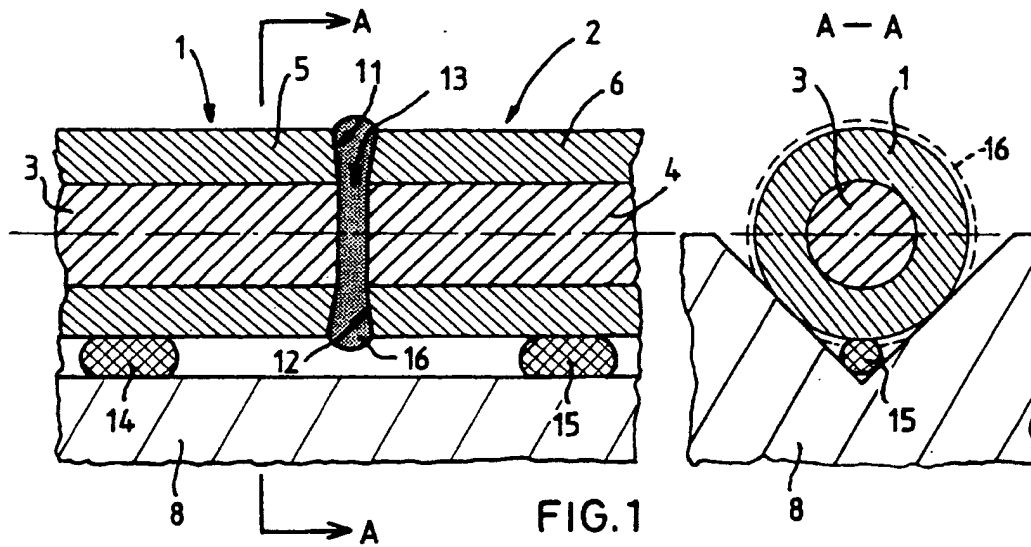


FIG. 4

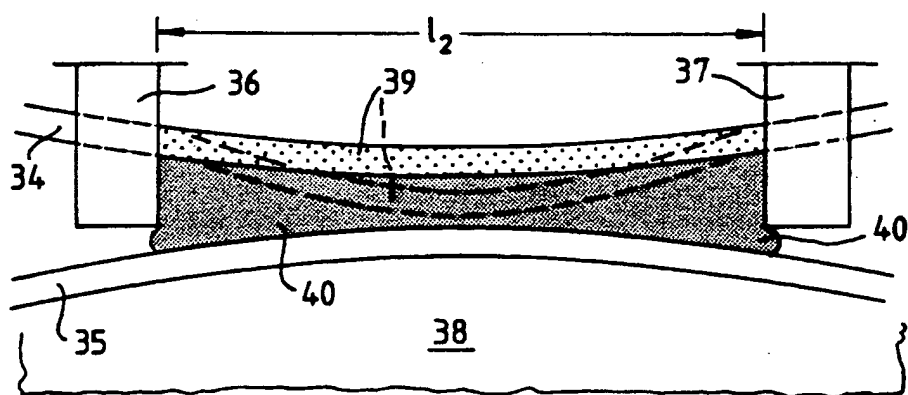
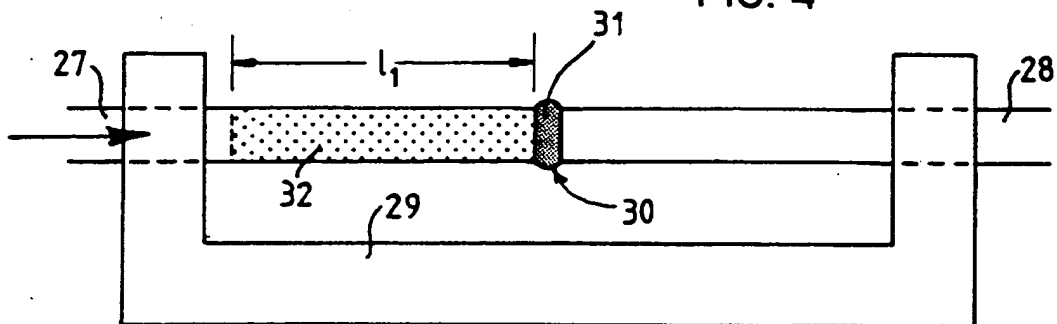


FIG. 5

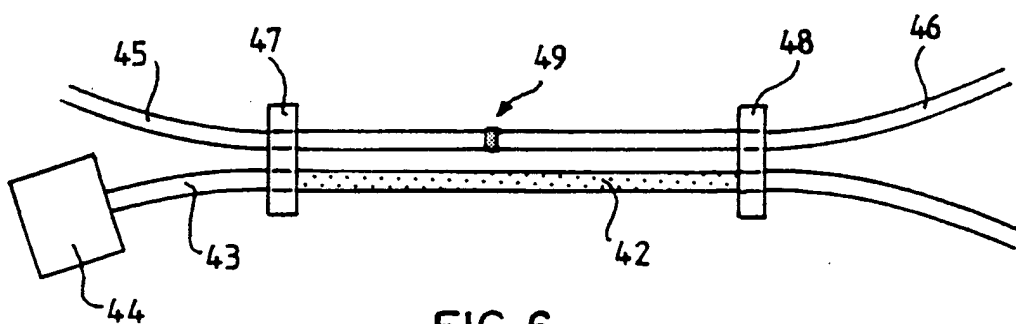


FIG. 6

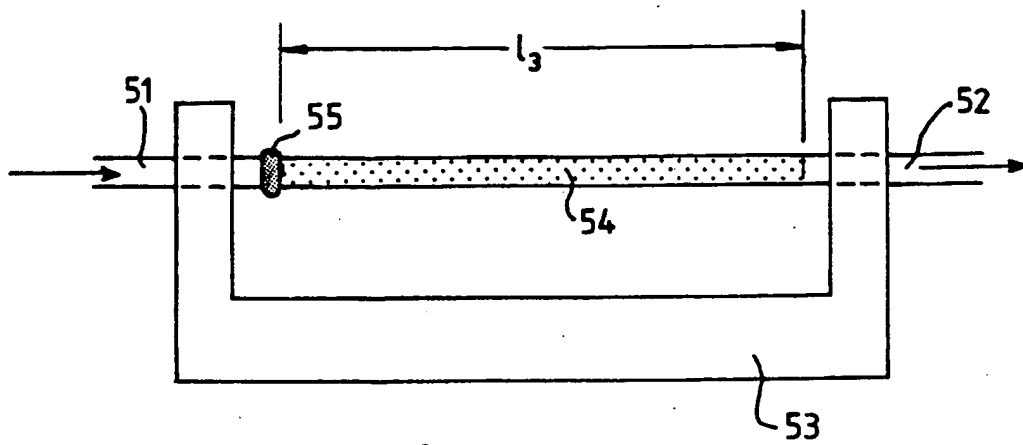


FIG. 7

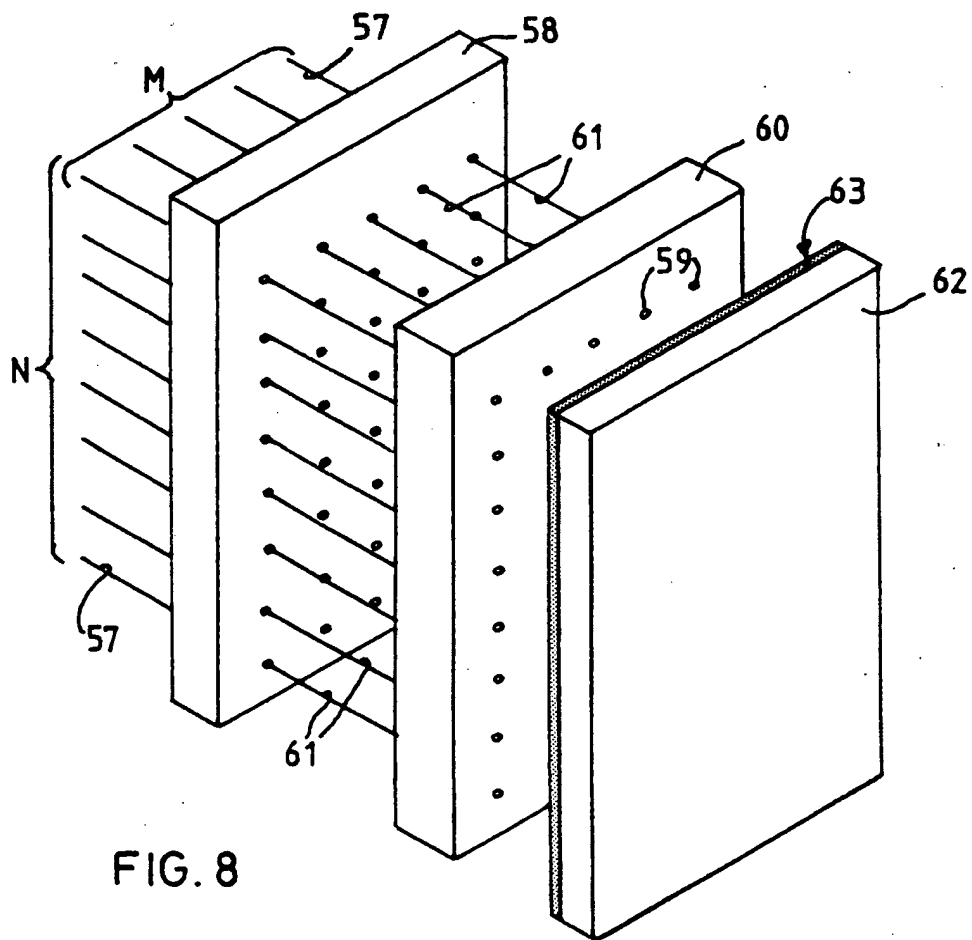


FIG. 8



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Application Number

EP 92 81 0814

Page 1

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A	PATENT ABSTRACTS OF JAPAN vol. 5, no. 177 (P-89)(849) 26 August 1981 & JP-A-56 107 202 * abstract * ---	1,6	
A	PATENT ABSTRACTS OF JAPAN vol. 8, no. 171 (P-293)8 August 1984 & JP-A-59 065 801 ( NIPPON DENKI ) * abstract * ---	1,2	
A	FUJITSU-SCIENTIFIC AND TECHNICAL JOURNAL vol. 27, no. 4, December 1991, KAWASAKI JP pages 369 - 378 N. WAKATSUKI ET AL. 'Moving-Fiber Optical Switch Using LiNbO3 Piezoelectric Actuator' * the whole article * ---	1,8	TECHNICAL FIELDS SEARCHED (Int. Cl.5)  G02B G02F
A	TOPICAL MEETING ON PHOTONIC SWITCHING, Incline Village, Nevada, 18-20 march 1987, Optical Society of America, Washington, S.R. Mallinson et al.: 'An All-Fibre Routing Switch', page 55-57 * the whole article * ---	1,8,10	
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The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 25 JUNE 1993	Examiner LUCK W.S.
<b>CATEGORY OF CITED DOCUMENTS</b> X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document  T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ..... & : member of the same patent family, corresponding document			



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## EUROPEAN SEARCH REPORT

Application Number

EP 92 81 0814  
Page 2

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The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 25 JUNE 1993	Examiner LUCK W.S.
<b>CATEGORY OF CITED DOCUMENTS</b> X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document  T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ..... A : member of the same patent family, corresponding document			